Longitudinal RF capture and acceleration simulation in CSNS RCS

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Abstract China Spallation Neutron Source (CSNS) is a high power proton accelerator-based facility. Uncontrolled beam loss is a major concern in designing the CSNS to control the radioactivation level. For the Rapid Cycling Synchrotron (RCS) of the CSNS, the repetition frequency is too high for the longitudinal motion to be fully adiabatic. Significant beam loss happens during the RF capture and initial acceleration of the injection period. To reduce the longitudinal beam loss, beam chopping and momentum offset painting methods are used in the RCS injection. This paper presents detailed studies on the longitudinal motion in the RCS by using the ORBIT simulations, which include different beam chopping factors, momentum offsets and RF voltage optimization. With a trade-off between the longitudinal beam loss and transverse incoherent tune shift that will also result in beam losses, optimized longitudinal painting schemes are obtained.

Key words beam loss, RF capture and acceleration, longitudinal painting scheme

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1 Introduction

The China Spallation Neutron Source (CSNS) project is proposed to provide a multidisciplinary platform for scientific research and applications based on neutron scattering techniques[1—3]. It is an accelerator-based facility with a proton beam power of 100 kW and a repetition rate of 25 Hz. The high beam power proton accelerator complex consists of an 80 MeV linac as injector and a 1.6 GeV rapid cycling synchrotron (RCS) as the main accelerator.

One of the primary concerns in designing high-intensity proton facilities such as the CSNS is the radio-activation caused by uncontrolled beam loss that can limit the machine's availability and maintainability. Proton synchrotrons with low beam power usually have a beam loss rate as high as several tens of percent, mostly occurring during the injection, initial RF capture, and at the time of transition-energy crossing[4]. The design of the CSNS RCS injection system has been attempting to reduce the beam loss by increasing the beam emmittance and beam uniformity to alleviate the transverse space charge effects[5, 6]. This study is devoted to the longitudinal motion in the RCS. The beam loss due to the RF capture, acceleration and the bunch factor is the dominance to determine the longitudinal injection mode and the RF pattern in the RCS.

2 RF capture and acceleration in the RCS

In the RCS, the RF cycle can be divided into four periods (see Fig. 1): injection, RF capture, acceleration and switched-off after extraction. Significant beam loss usually occurs during the RF capture (before the first critical point in Fig. 1) if the beam is injected and accumulated in a coasting mode. The second critical point is at the mid-acceleration when the phase space acceptance decreases due to large synchronous phases that are needed for the fast acceleration. With a maximum RF voltage of 168 kV, the synchronous phase will reach to about 45°.

The RF capture process is adiabatic if its duration is long enough compared with the synchrotron period T_s, which is usually true in the case of slow cycling synchrotrons. With an adiabatic capture, the capture efficiency is high and the dilution in the longitudinal

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emittance due to the filamentation effect is small. At the injection energy, a stationary bucket is created with a synchronous phase at zero. The initial stable phase space area is small with respect to the dimensions of the unbunched beam. The RF voltage is then progressively increased until the bucket acceptance is sufficiently large to accommodate the entire beam. The captured beam will become bunched once the synchronous phase φ_s is moved away from zero and the acceleration begins. Theoretically, a small longitudinal emittance dilution due to the filamentation effect in the synchrotron phase space can be formed by adiabatically ramping the RF voltage with $\varphi_s=0$[7], and this will result in a very little beam loss during the later acceleration. However, in a rapid cycling synchrotron such as the CSNS RCS, the adiabatic condition does not hold really and a large emittance dilution will happen. The high repetition frequency of the RCS leaves little time for the RF capture to be fully adiabatic if the RF capture process starts from a coasting beam, as the magnetic field is changing. The voltage amplitude of the ring RF system must be programmed according to the increasing synchronous phase to ensure a sufficiently large RF bucket area to minimize particle losses at the same time to keep the acceleration pace throughout the RF cycle. Other methods such as a chopped beam injection are helpful to reduce the beam loss during the RF capture. We will study both continuous and chopped beam injections in an effort to look for a compromised scheme.

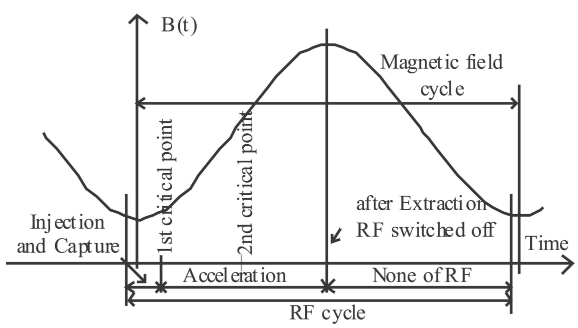

Fig. 1. Magnetic field and RF cycle.

The parameters that define the capture process are chosen in order to satisfy three criteria: The capture efficiency must be as close as possible to unity; The longitudinal emittance dilution must be minimum; The bunch factor must be large to reduce the transverse tune shift.

In a synchrotron, the energy gain per revolution is linked to the ramping speed of the magnetic field $\dot{B}$ in dipole magnets by

$$V \sin\varphi_s = 2\pi R\rho\dot{B}\,, \tag{1}$$

where R is the mean radius of the ring, ρ is the radius of curvature in dipole magnets[7].

In a rapid cycling synchrotron, a cosine-like magnetic field with respect to time has to be used as a White circuit power supply system is necessary to save the energy and alleviate the impact of very sharp load to the electricity network[8]. To keep the acceleration in pace with the ramping magnetic field that increases from the lowest level at the injection to the highest level at the extraction with the maximum ramping speed at the mid-acceleration, the RF voltage and the synchronous phase should vary according to Eq. (1). The choice of the maximum RF voltage and the largest excursion φ_s is a compromise between the cost of the RF system with a higher voltage and the beam loss increase with a large φ_s. A large synchronous phase means the shrinking of the bucket area. In the preliminary design, the maximum RF voltage of 168 kV and the maximum synchronous phase of 45° have been chosen. However, the detailed RF voltage and synchronous phase patterns, together with a good longitudinal injection scheme, are still very important to minimize the beam loss. At the same time, the longitudinal motion is linked to the transverse motion by the bunch factor that affects the transverse tunes by the space charge and to the increase in momentum spread during the acceleration, which can also result in beam loss. The RF voltage starts from a very low level and increases progressively during the injection and the initial RF capture until the first critical point (large beam loss). Then the voltage will increase rapidly and the synchronous phase will increase modestly to keep pace with the magnetic field. After the voltage reaches the maximum, the synchronous phase will continue to increase until the second critical point where both the ramping speed of the magnetic field and the synchronous phase reach the maximum. The last part of the acceleration cycle is usually less critical in the design; sometimes the beam extraction has some special requirements.

On the other hand, the RCS RF system design concerns not only the maximum RF voltage but also the RF voltage limitation, say about 100 kV in the first milliseconds due to the disfavored frequency range for the ferrite-loaded cavities. Therefore, all the studies on the longitudinal motion are based on these conditions.

3 Simulation results and discussion

3.1 Simulation with ORBIT

Due to the nature that the longitudinal motion is independent of the transverse motion in proton synchrotrons, here we carry out simulations only on the longitudinal motion. However, the longitudinal motion has an impact on the transverse motion as mentioned above, thus the longitudinal studies also cover the impact before we take full-3D simulations. The code ORBIT[9] has been used for the beam dynamics simulations including the space charge effect in the RCS. It can perform simulations either on the 1D longitudinal motion or on the 2D transverse motion or on the 3D motion. The main parameters for the longitudinal simulations are given in Table 1.

Table 1. Machine parameters and beam parameters.

circumference/m	230.8
Injection energy/GeV	0.08
extraction energy/GeV	1.6
repetition rate/Hz	25
harmonic number	2
transition energy	4.976
average machine radius/m	36.73
bending radius/m	8.021
magnetic field/T	0.16—0.98
accumulated protons	1.88×10^{13}
injection peak current/mA	15
injection phase distribution	uniform
injection momentum spread	$\pm 0.1\%$
injection momentum distribution	Gaussian

3.2 Injection with different chopping factors

As mentioned in Section 2, the continuous beam injection scheme has relatively low RF capture efficiency, thus the injection with a chopped beam has been also studied. The purpose of chopping the beam is to create a macro-time structure in the linac beam by a chopper in the linac front-end so that the macro pulse can fit properly into the RF buckets in the RCS. Herein, the chopping factors of 100%, 90%, 83%, 75%, 60% and 50% are used for simulations, where the chopping factor is defined as the ratio of macro bunch full length to RCS RF voltage wave length at the bottom of the magnetic field, i.e. smaller chopping factor means more beam is chopped. Fig. 2 shows the simulation results of the beam loss and the transverse tune shift are dependent on the chopping factor. More particles are lost as the chopping factor increases. However, beam chopping does increase the transverse tune shift, especially in the injection period. The transverse tune shift $\Delta\nu$ can be calculated by the following formula[10]:

$$\Delta\nu = -\frac{r_{\mathrm{p}} n_{\mathrm{t}}}{2\pi\beta^2\gamma^2\varepsilon B_{\mathrm{f}}} \qquad (2)$$

here $r_{\mathrm{p}} = 1.53\times10^{-18}$ m is the classical radius of proton, n_{t} is the accumulated particles in the RCS, β and γ are the Lorentz's relativistic factors, ε is the transverse emittance and B_{f} is the bunch factor.

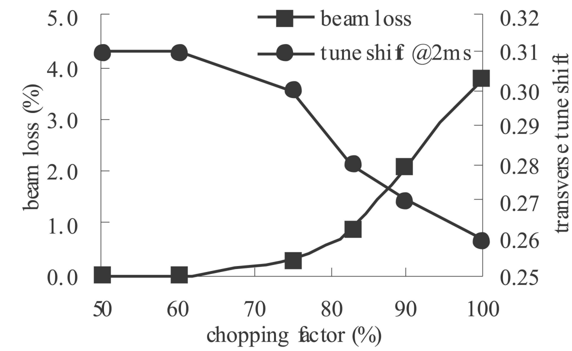

Fig. 2. Variations of the longitudinal beam loss and the transverse tune shift with the chopping factor (2 ms is the time after the minimum magnetic field).

3.3 Momentum offset painting

If the beam from linac is injected into just the center of RF bucket of RCS, the charge intensity at the bucket center becomes fairly high, and the transverse tune shift becomes very large. Injection with a momentum offset can avoid such problem. With a momentum offset, the longitudinal painting will form

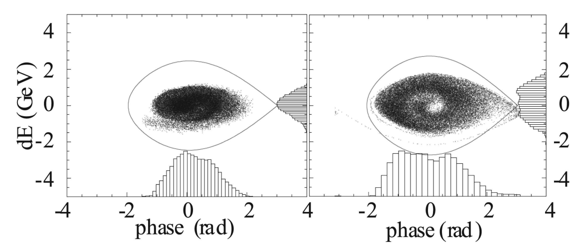

Fig. 3. Beam distribution after beam injection with the chopping factor of 50%. left: no momentum offset; right: momentum offset of 0.6%.

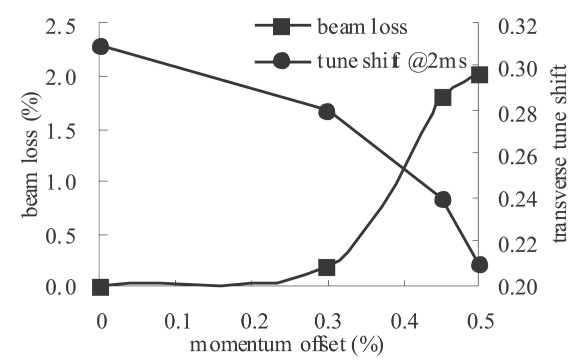

Fig. 4. Variation of beam loss and transverse tune shift with momentum offset at the chopping factor of 60%.

a hollow beam and the charge intensity along the bunch length will become flattened (see Fig. 3). Fig. 4 shows the simulation results of the beam loss and transverse tune shift with momentum offsets of 0%, 0.3%, 0.45% and 0.5%. Here, the chopping factor is 60%. A larger momentum offset will result in a larger beam loss but will efficiently decrease the transverse tune shift.

3.4 Optimized schemes

The simulation results show that both the beam chopping and the momentum offset painting methods have absolutely contradictory effects on the longitudinal beam loss and the transverse tune shift. This indicates an optimized longitudinal injection scheme should be a compromise between the longitudinal beam loss and the transverse tune shift. If the maximum longitudinal beam loss is limited by 2%, the maximum momentum offsets and corresponding transverse incoherent tune shifts are listed in Table 2 for different chopping factors. Both the chopping factor of 60% with a momentum offset of 0.50% and the chopping factor of 50% with a momentum offset of 0.60% look to be promising longitudinal painting schemes. However, when the proton traversal in the stripping foil is considered[5], a larger chopping factor such as 75% or 83% also can be considered.

Table 2. Comparison of longitudinal painting schemes.

chopping factor	momentum offset	maximum transverse tune shift
100%	0.0%	0.29
90%	0.0%	0.30
83%	0.28%	0.26
75%	0.33%	0.26
60%	0.50%	0.23
50%	0.60%	0.23

4 Conclusion

The RF capture and acceleration processes in the CSNS RCS are simulated by using the ORBIT code. The optimized longitudinal painting schemes based on the injection with a chopped beam and off-momentum to control the longitudinal beam loss and reduce the transverse tune shift are given. The present study only focuses on the longitudinal motion. The negative time injection is still under way. Future work will be fully three-dimensional by involving transverse phase space painting and the correlativity between the transverse and longitudinal motions.

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